Fermilab
Run II Performance

RHIC Retreat, June 15-17 2005

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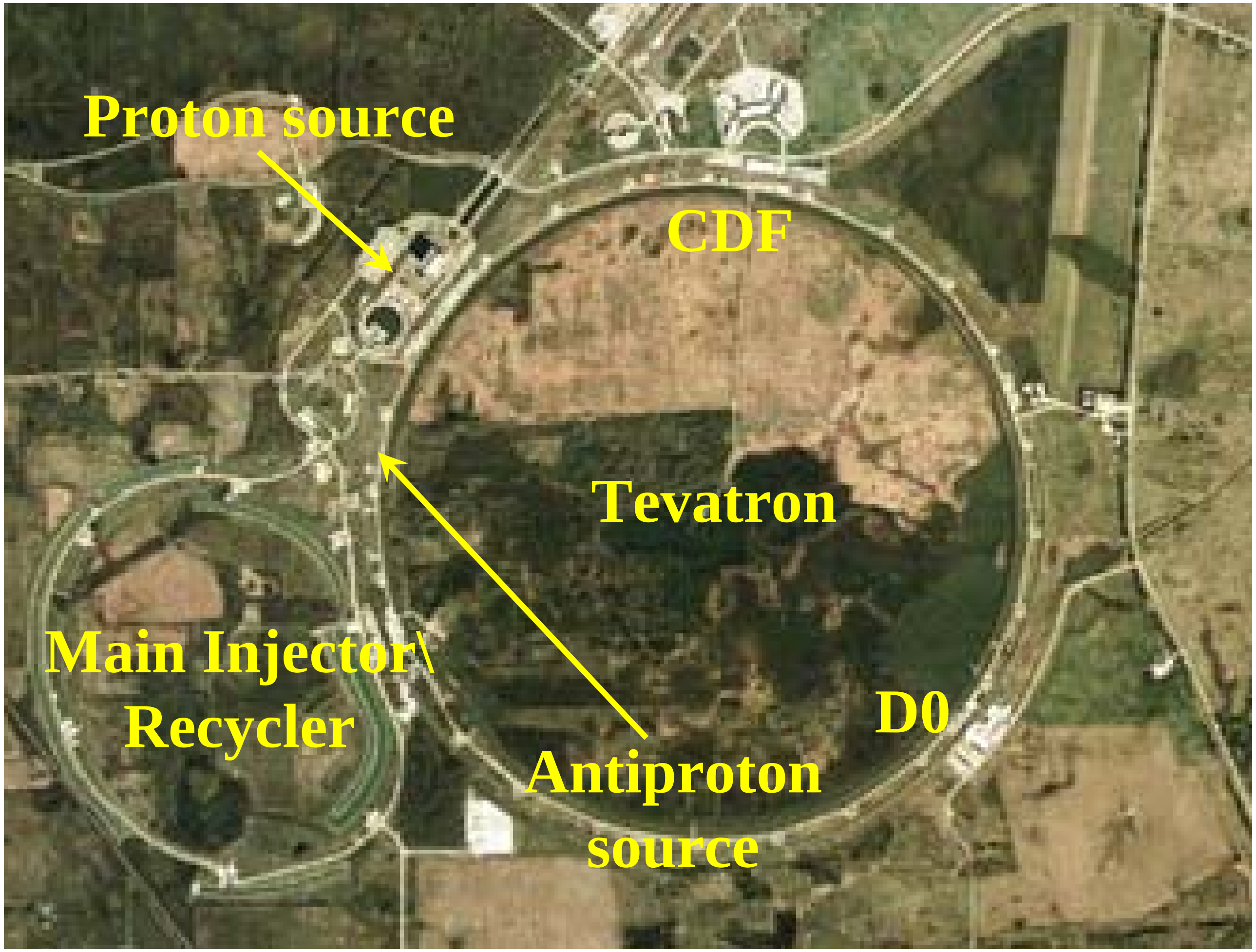
Fermilab Accelerator Division

Some similarities and differences between RHIC and the Tevatron

- Both are Colliders with multiple experiments, halo removal, beam-beam etc.
  - Ions vs. proton-pbar
  - Fermilab has longer stores, but similar percentage of up-time and physics hours
  - Duration of runs (Typically 40 weeks for the Tevatron)
    - Fermilab shutdowns have extreme time pressure and are driven by upgrades
  - Run II is expected to end when the LHC begins taking physics data
- The Tevatron runs very close to its quench limit
- Demands on accelerators in addition to collider operations
  - FNAL injection chain required to run continually
- Roll of Run Coordinator
  - Fermilab Run Coordinator similar to RHIC's, but also
    - Handles scheduling duties including accelerator and experimental accesses (including filtering)
    - Schedules store parameters and duration as well as study periods
  - Needs to communicate plan to all interested parties
- Need to increase luminosity without too much disruption
- We have one experiment (CDF) more sensitive to backgrounds than the other (D0)
  - Our goal is to maximize integrated luminosity to tape for both experiments
- Beam position control and correction crucial
  - It was beneficial for us to instrument our low beta quadrupoles
- We worry about our budget, manpower and future too

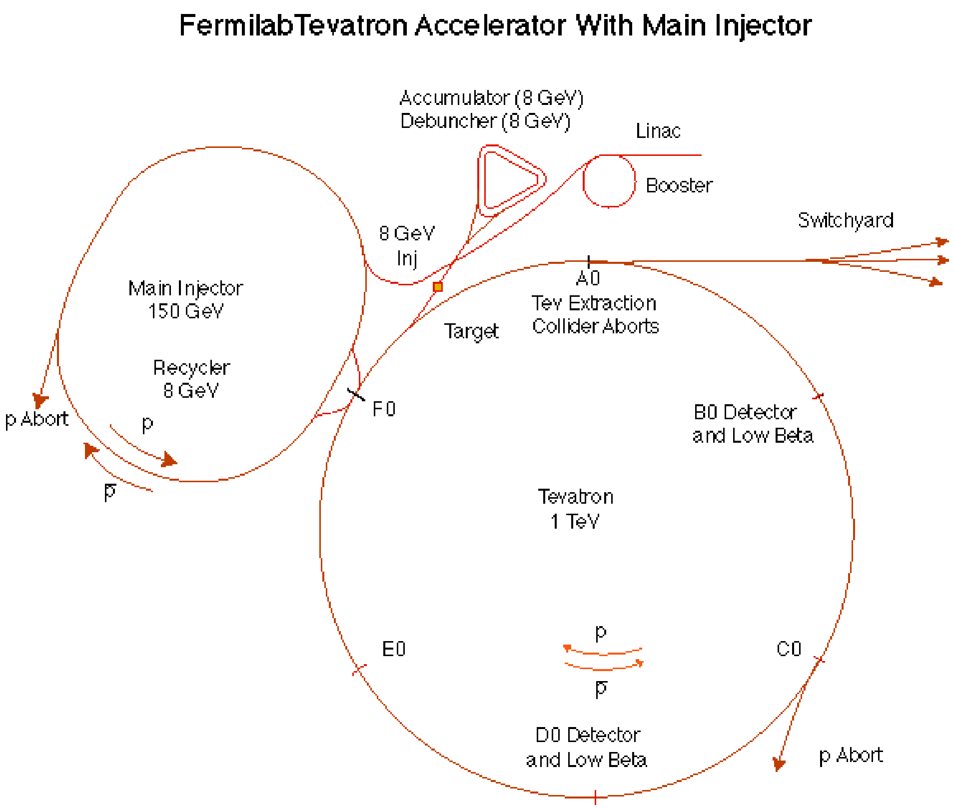
Fermilab Complex

- The Fermilab Collider is a Antiproton-Proton Collider operating at 980 GeV



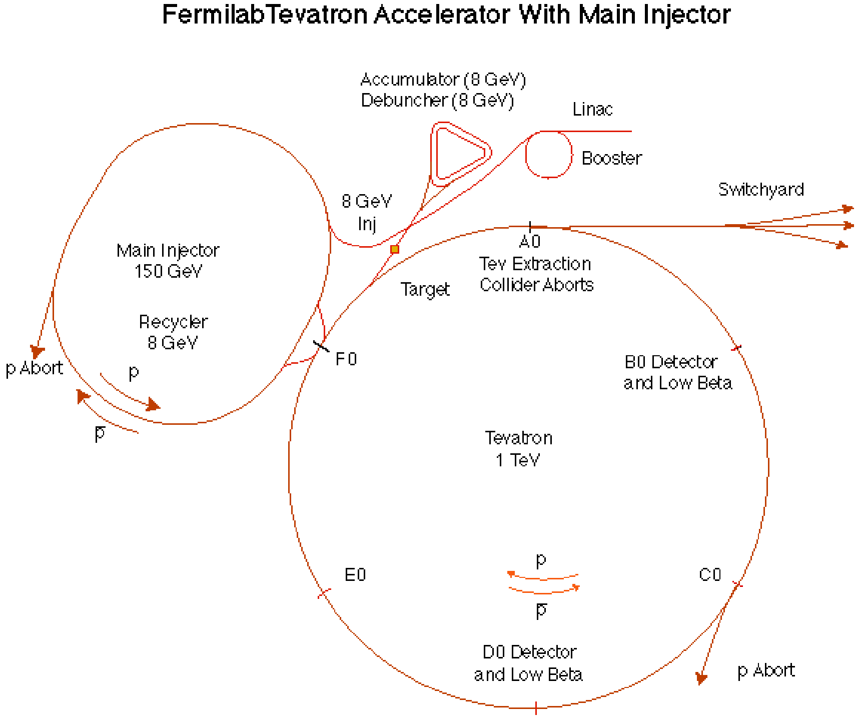
Proton Acceleration

- H- ions are accelerated to 750 keV in the Crockoft-Walton
- H- ions are accelerated to 400 MeV in the Linac
- H- ions are stripped and multi-turn injected onto the Booster
- Protons are accelerated from 400 MeV to 8 GeV in 33 mS in the Booster
- In the Main Injector Protons are accelerated from 8 GeV
  - to 120 GeV for NuMI operation and pbar production in 2.0 - 4.0 seconds
  - to 150 GeV for Tevatron filling in 3.0 seconds
  - to Switchyard, resonantly extracted for two fixed target users
- Protons are accelerated from 150 GeV to 980 GeV in the Tevatron

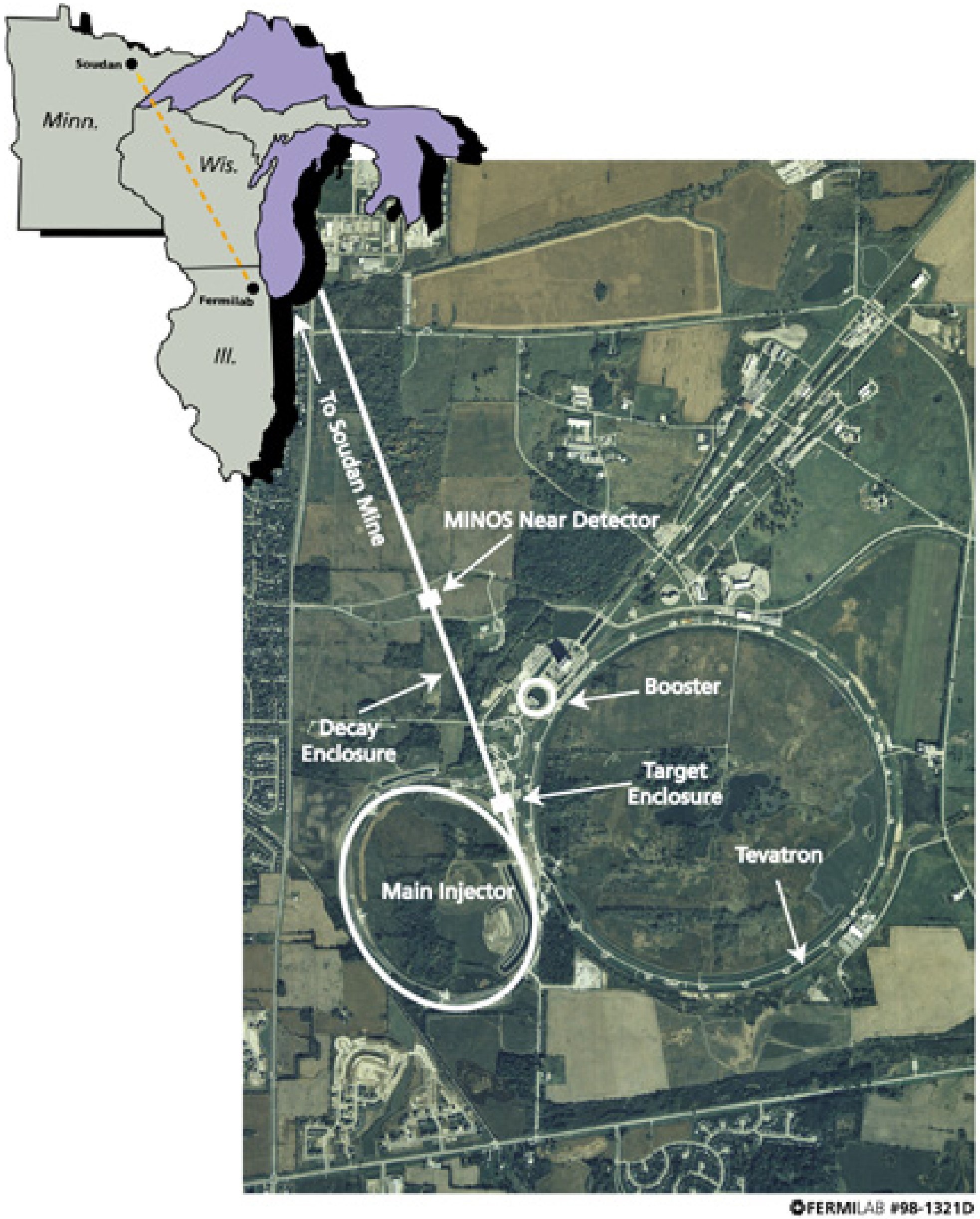


Pbar production

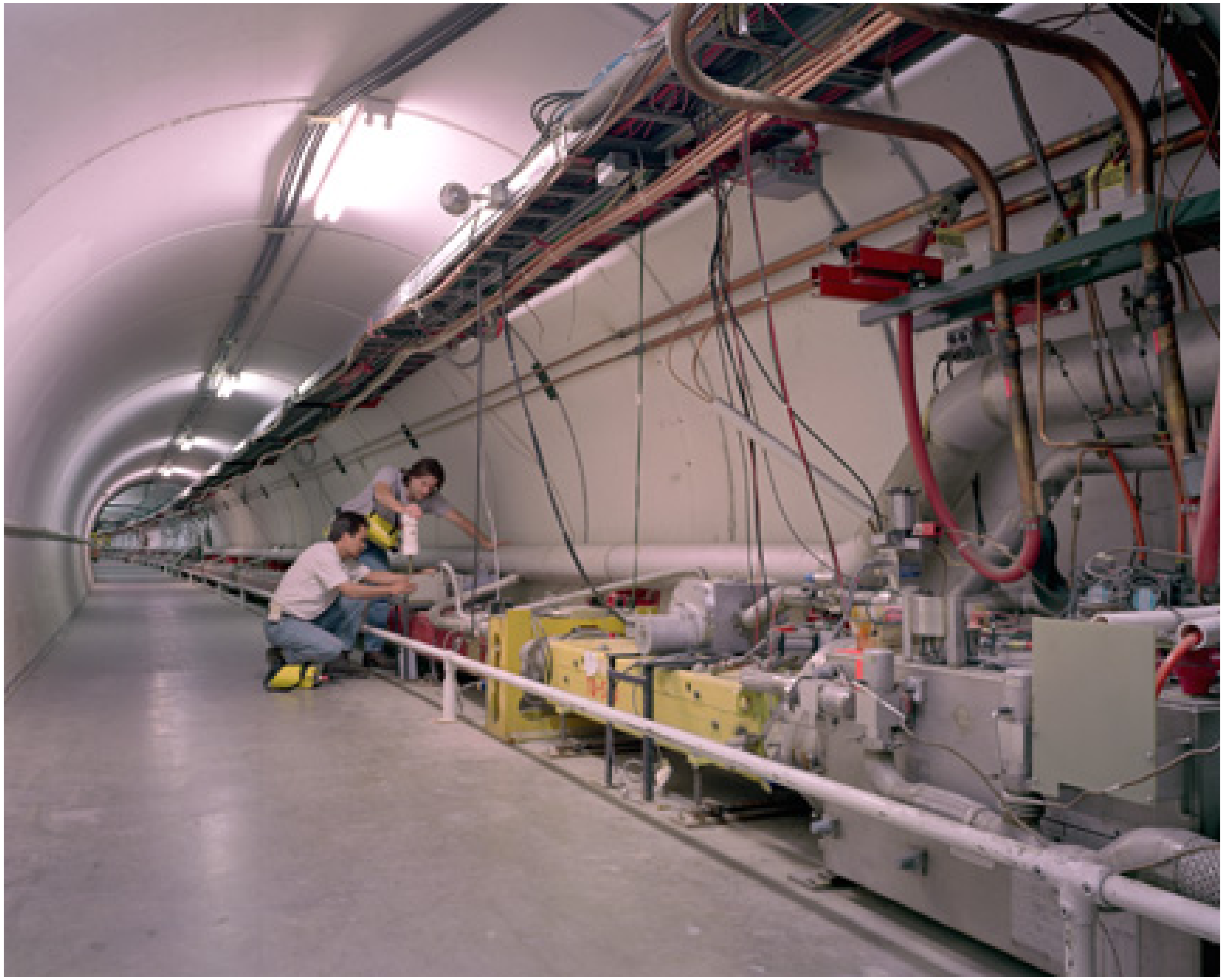
- 1×10^8 8 GeV pbars are made every 2-4 seconds by delivering 7×10^{12} 120 GeV protons onto an Inconel target
- 8 GeV Pbars are focused with a lithium lens operating at a gradient of 760 Tesla/meter
- 30,000 pulses of 8 GeV Pbars are collected, stored and stochastically cooled in the Debuncher and Accumulator and Recycler Rings
  - The stochastic stacking and cooling increases the 6-D phase space density by a factor of 600×10^6
- 8 GeV Pbars are accelerated to 150 GeV in the Main Injector and to 980 GeV in the Tevatron (36p x 36pbar)



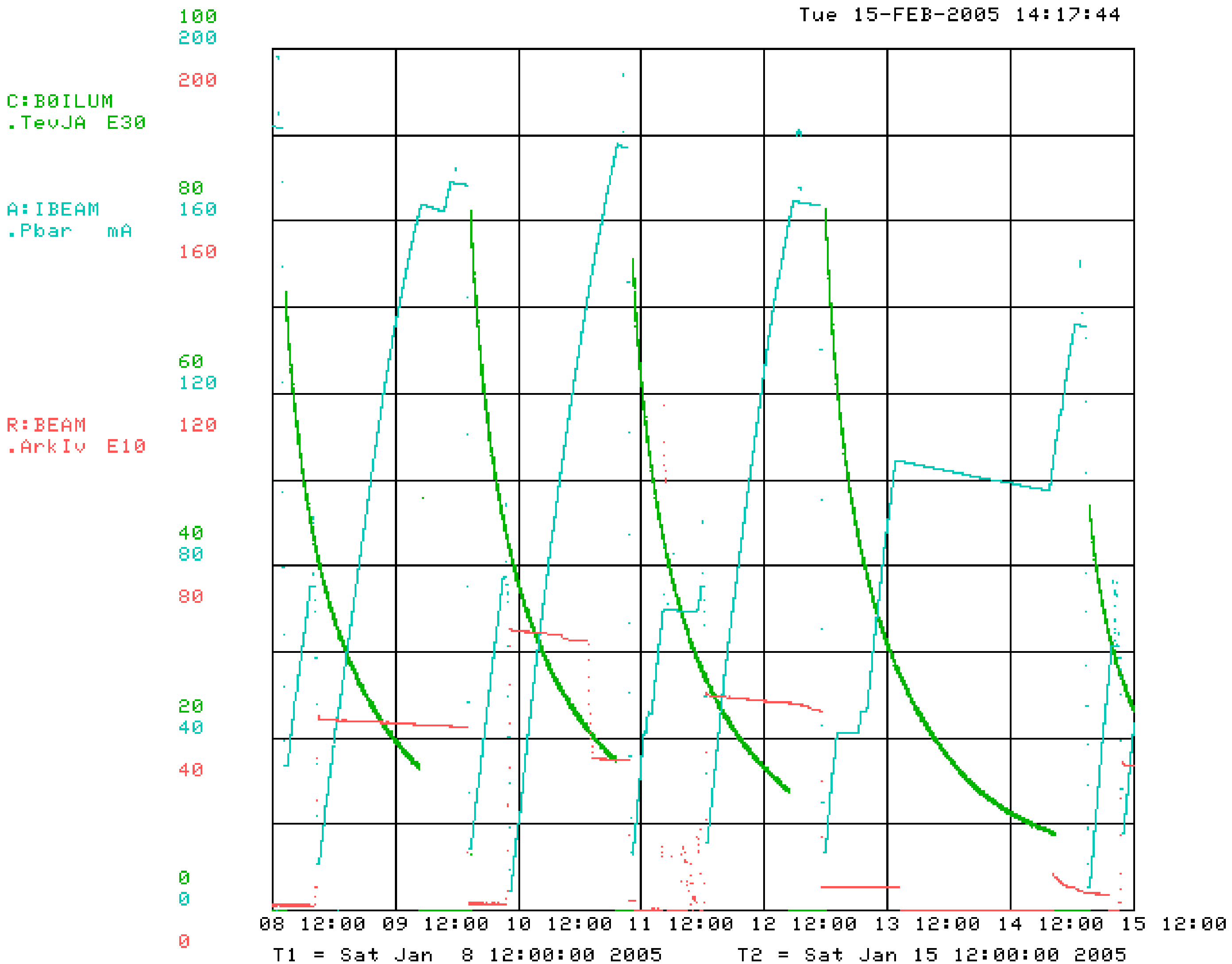
NuMI/MINOS


Soudan
Minn.
Wis.
Fermilab
Ill.
To Soudan Mine
MINOS Near Detector
Booster
Decay
Enclosure
Target
Enclosure
Tevatron
Main Injector
©FERMILAB #98-1321D

Tevatron tunnel



Collider stores over a week



Collider History

- 1986-1987 Engineering Run
  - .05 pb^{-1}
- 1988-1989
  - 9.2 pb^{-1}
- Run Ia (1992-1993)
  - 32.2 pb^{-1}
- Run Ib (1994-1996)
  - 154.7 pb^{-1} (196 pb^{-1} cumulative)
- Run II (2002-2009)
  - 4,000 – 8,000 pb^{-1} planned

Changes for FY04

- Run had been in a "commissioning" mode in FY02 and FY03
  - Emphasis was on providing study time to meet goals
  - Progress had been well below expectations (and the run was 25% over)
- Philosophy shift to considering the Collider commissioned
  - Focus changed to operating the Collider
    - Study time was primarily devoted to improving machine performance (present and future)
      - Studies required a plan and purpose
      - Study time was scheduled to minimize the impact on operations
    - Shutdowns and accesses were kept as short as possible
      - Emphasis on improving performance and reliability
  - Most aspects of operating the accelerators had become routine
- The competition for beam, study time, and resources between the Collider and external beam lines increased significantly in FY04
  - Recycler was being commissioned
  - MiniBoone was operational
  - SY120 became operational
  - NuMI was gearing up to start commissioning in early FY05
- Provide long-term continuity for operational goals, strategy and monitoring.
- Improve/clarify assignments of responsibility for
  - study strategy and coordination
  - machine parameter targets
  - shot strategy
- Involve experiments directly in the decision-making process

Changes for FY04 and the future

- The task for coordinating the operations of the accelerators in FY04 became the permanent responsibility of the new Integration Department.
- The leader of the Integration Department is the Associate Division Head for Systems, Operations, and Integration.
- This Integrations Department is divided into four wings
  - Operations Coordination
  - Shot Analysis and Strategy
  - Accelerator Physics and Accelerator Studies
  - Rapid Response Team
- The Operations Department will assume more responsibility for operating the accelerators
  - Larger reliance on Crew Chief decision making (as in the latter part of Run I)
  - Run Coordinator provides guidelines for Crew Chief
- Improved communication between the Run Coordinator and Experiments
  - Experiments participate in daily Integration Meeting
  - Run Coordinator elog used to disseminate information
- Future changes
  - Run Coordinator becomes three-person team
    - A second deputy RunCo has been recently added
    - In FY06, the deputies will take on the day to day responsibilities
    - I'll be the team leader, concentrating on shot analysis, operational and studies priorities
- Associate Division Head becomes more involved in problem areas
  - Will lead Rapid Response Teams when appropriate
  - Has been involved with planning what happens after Run II
- Rapid Response team may merge with Accelerator Physics

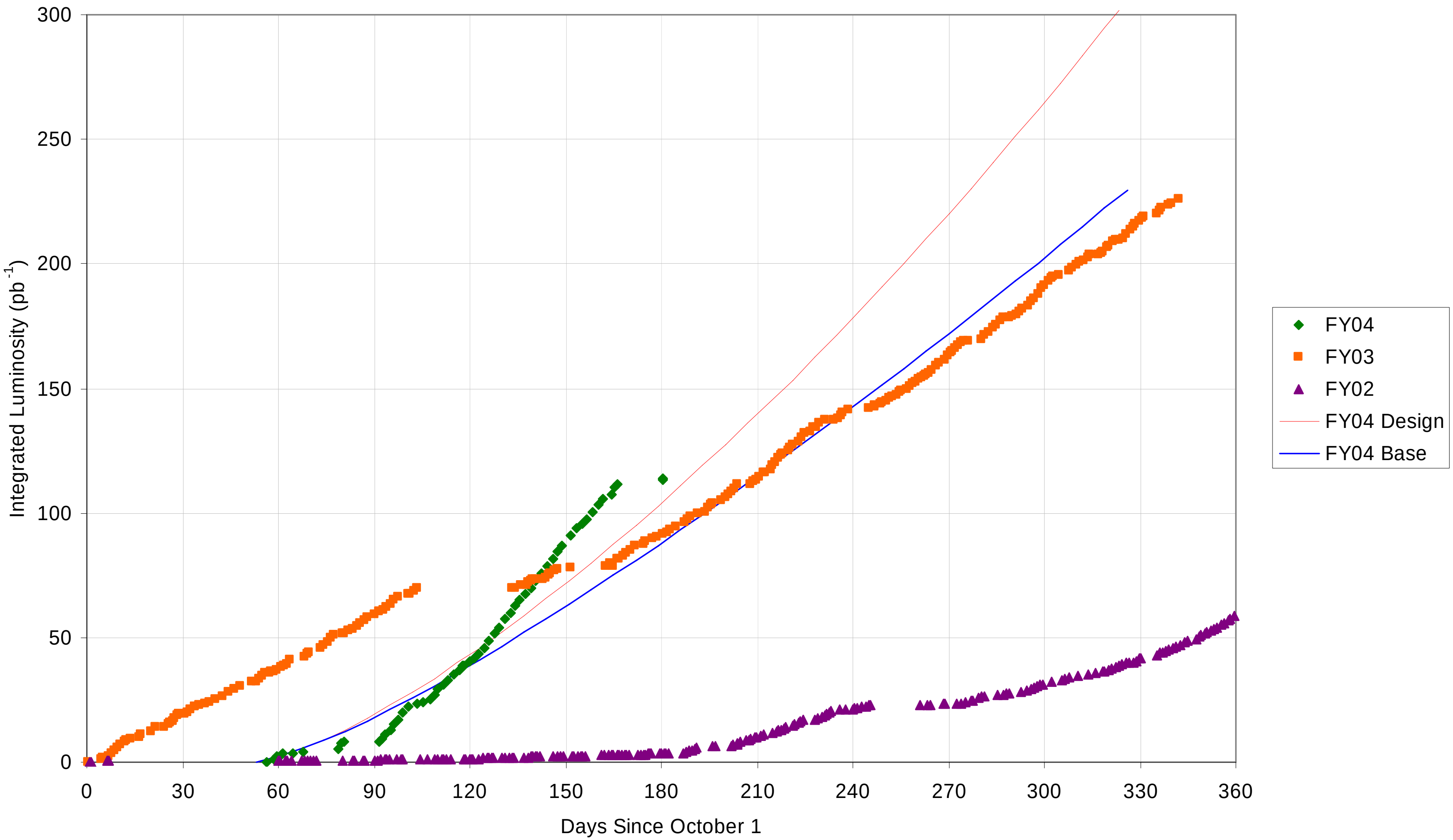
Run Coordinator's Responsibilities

- Create and coordinate the operational planning for the accelerator complex
  - Run daily Integration Meeting to discuss and formulate the operational plan
  - Schedule Recycler and Colider transfers
  - Coordinates studies and commissioning activities
    - Tevatron and accelerators, SY120, Recycler, Ecool and NuMI
      - Also NTF, MTA and MuCool
  - Schedule accelerator studies
  - Schedules shutdowns and maintenance
  - Evaluates and oversees operational policies of Systems Departments
  - Monitors peak operating performance of the accelerators
  - Receives and coordinates requests from the experiments
- Operational planning and coordination now the primary focus
  - Long range planning and presentations are handled by Associate Division Head
  - Creation of integration team reduces the burden on the Run Coordinator
- Uses input from other groups within the Integration Department in decision making
  - Shot analysis, evaluating studies requests etc. is now a group effort
- Run Coordinator is no longer a 4-month term
  - Provide long-term continuity for operational goals, strategy and monitoring
  - Part of the work load is shifted to other members of the Integration and Operations Departments

Communications

- The primary tool for communications is the DAILY Operations Meeting
  - This meeting
    - Is short (20-30min) and focused
    - Has a well defined agenda and goals
  - To keep communication open and direct, attendance to this meeting is limited
    - At most 2 representatives from each system in which one is the machine coordinator
    - At most 2 representatives from each support department
    - At most 2 representatives from each experiment
    - The Friday meeting is open to anyone and also has weekly reports from the various machines
  - At the end of the meeting the systems, support departments, and the experiments know exactly when the plan for the day is
  - This plan is summarized as an entry in the Run coordinator elog for the rest of the lab to read
  - Changes in the plan are communicated via the MCR Operators and Run Coordinator elog
- An important basis for communications is Shot Data Analysis (SDA)
  - SDA
    - Rapidly identifies under (or over) performing systems
    - Is used for judging performance of systems at the daily operations meeting.
    - Is used for predicting future performance
    - Eliminates many conversations that begin with “I remember when we had a store that…”
    - A large number of standardized plots are produced daily and posted on the web
  - Important analysis
    - Single store snapshot
    - Parameters as a function of store number
  - SDA consists of
    - A dedicated database
    - Tools for setting up automated acquisition of data into the data base
    - Tools for retrieving data from the database

Luminosity projection for FY04



Major Accomplishments in FY04

- Proton Source
  - Operational Improvements
    - Booster Aperture
      - Alignment of Booster cavities and Magnets
      - Long 3 septum
    - New dogleg magnets at Long 3
      - Removal of beta wave
      - Less tune shift
    - Damper mode number and Power increase
    - Matching of the 400 MeV Line
    - Harmonic Correction
    - Two stage collimation system
  - Records
    - Record intensities- 6.0×10^{12} protons/pulse
    - Record Efficiencies > 85%
    - Record Throughput
      - > 6.8×10^{18} protons/week
      - > 6.0×10^{16} protons/hour
      - > 4.5×10^{17} protons/shift
- Antiproton Source
  - Stacking rate 13.65×10^{10} pbars/hour
  - Largest stack 246×10^{10}
  - Longest sustained stack > 2 months
  - Debuncher Aperture Increase
  - Main Injector – Debuncher Phase alignment system
    - Aperture Increase
    - 8 GeV alignment across the injector complex now possible

Major Accomplishments in FY04 (cont.)

- Recycler
  - Recycler bake-out was extremely successful
    - Transverse emittance growth reduced by a factor of 4-5
  - Recycler shots to the Tevatron
    - Initial Luminosity > $17 \times 10^{30} cm^{-2} sec^{-1}$
    - Integrated useable luminosity
  - Stack of >150×10^{10} pbars in the Recycler
  - Recycler was put into Mixed Source operations
  - Recycler was ready for Electron Cooling
- Tevatron
  - Lifetime at 150 GeV
    - Larger Aperture, alignment and dipole un-rolls
    - Use of Octupoles to control differential chromaticity
  - Emittance dilution reduced
    - Smart bolt retrofit -> de-coupling at TEV injection
    - Optimization of injection optics
  - CDF IP
    - Location of IP was 4-5 mm too high vertically
    - Significant impact on CDF's
      - Silicon tracking efficiency
      - SVX longevity due to radiation damage
    - Rapid response team was organized during the 1 week shutdown in early December (due to the 16 house quench) to find a solution to move the CDF IP down by 4 mm
  - New Low Beta Optics
    - 20% increase in luminosity

FY04 Machine Issues

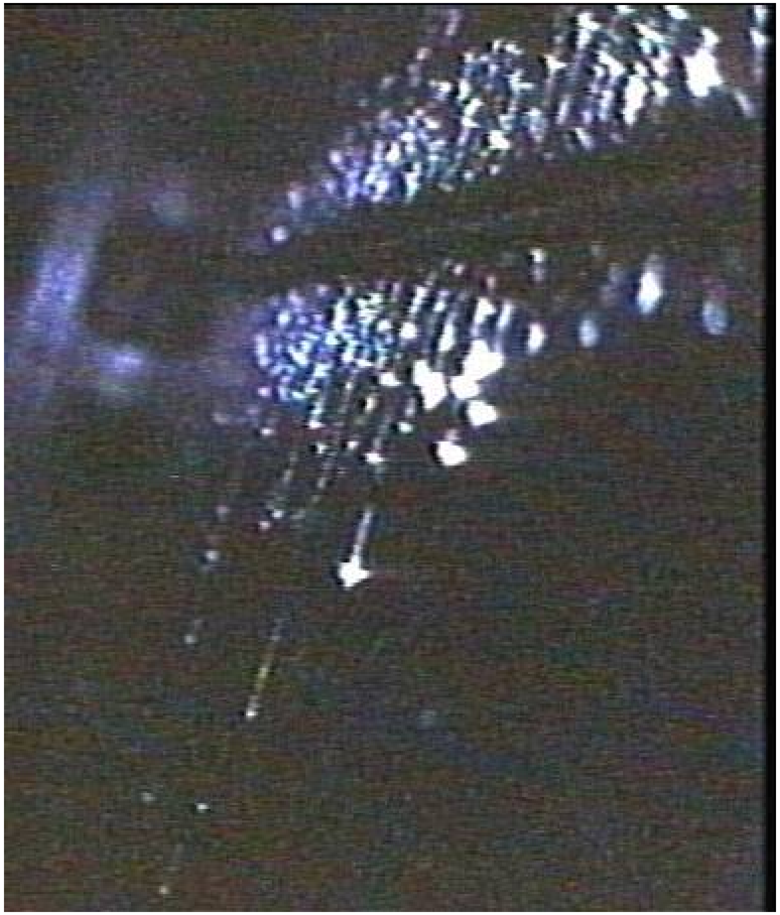
- Linac
  - Availability of low energy Linac RF Power tubes
  - Klystron spare viability
- Booster
  - Radiation damage due to the proton demands of the neutrino program.
    - Running at record throughput
    - Commissioning cogging (needed for slip-stacking and NUMI)
    - Preliminary stages of developing a proton plan
      - Pulse component upgrade
      - Aperture upgrade (RF stations and kickers)
      - Alignment upgrade (TEV style alignment network)
      - Closed orbit control (ramped magnets and power supplies)
- Pbar Production
  - Increase transverse aperture of AP-2 and the Debuncher
  - Greatly improve D/A transfer at fast cycle times
  - Minimized the Momentum Spread in the Debuncher
    - Increase the bandwidth of the Debuncher Momentum cooling system (~20%) with equalizers
    - Optimize gain and gain ramping in the Debuncher momentum cooling
    - Investigate a static change in gamma-t in the Debuncher
      - Trade-off of bunch rotation bucket are vs good mixing for the accumulator
    - Investigate the feasibility of ramping gamma-t in the Debuncher

FY04 Machine Issues (cont.)

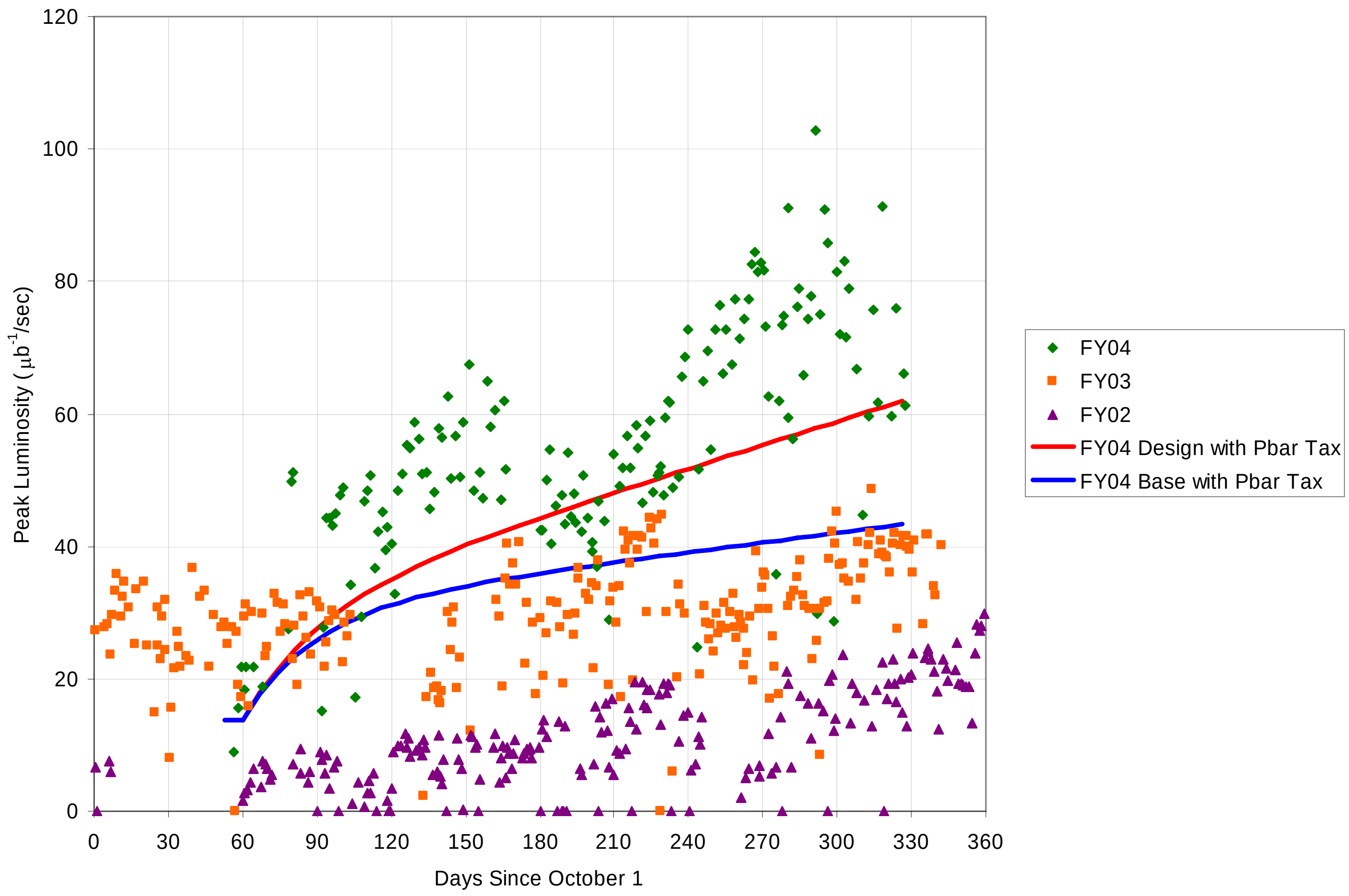
- Recycler
  - Transverse emittance growth is NO LONGER an issue
    - Recycler bake-out was extremely successful
      - Transverse emittance growth reduced by a factor of 4-5
  - Mixed Source Mode Operations
    - Injection and Extraction Transfer mechanics
    - Transverse stochastic cooling cooling rate
    - Longitudinal emittance dilution
      - During injection and extraction
      - During storing
    - Beam stability
- Tevatron
  - More magnet unrolls and cold lifts required during shutdown
  - Ready for additional separator to be installed during shutdown
    - Need to determine benefit of further upgrades
  - Improve protection to experiments and components from beam loss

FY04 Lessons

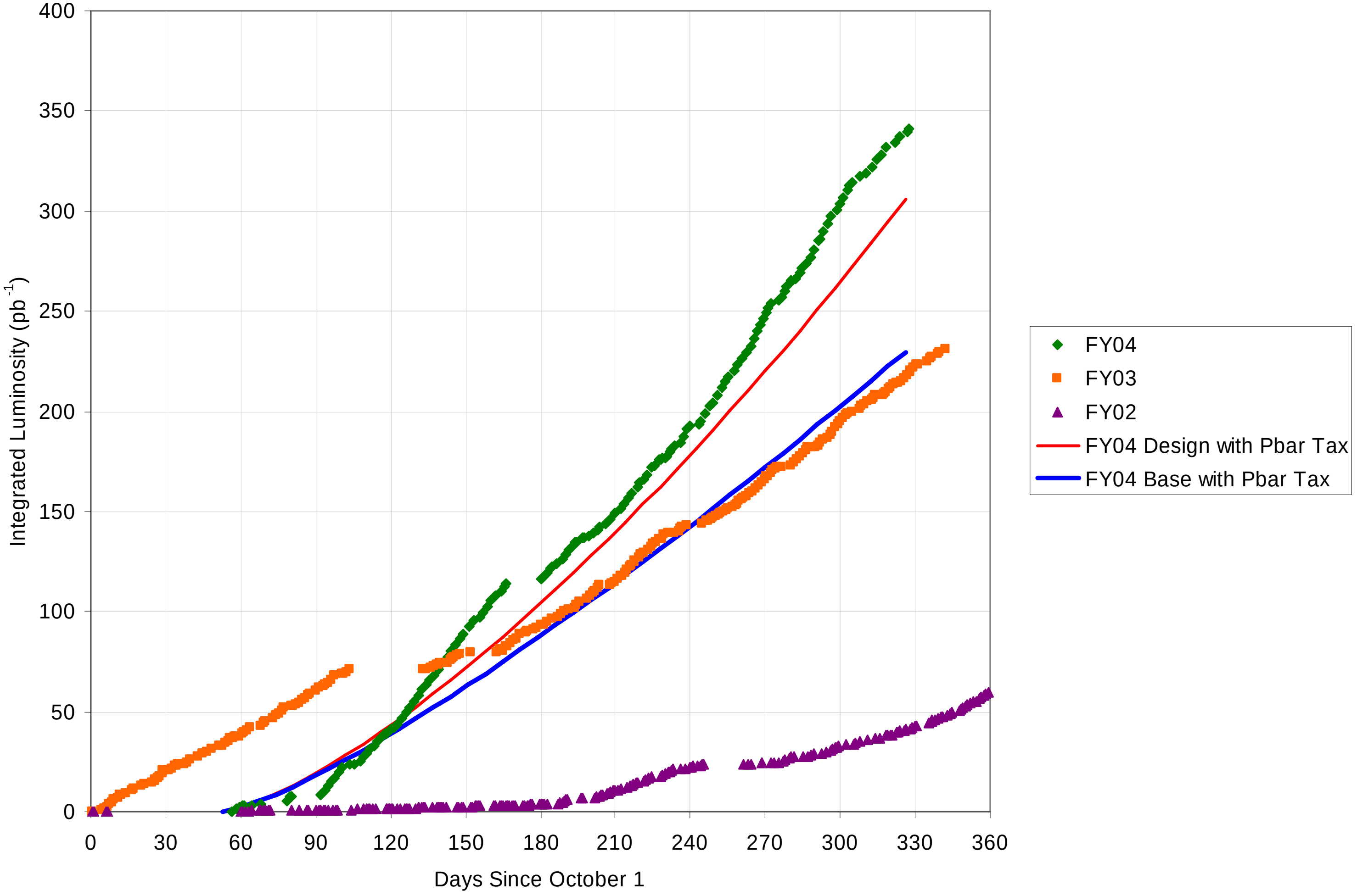
- Tevatron Abort
  - Because of the Experiments' silicon detectors, we cannot tolerate "messy" aborts
  - A single messy abort triggers a TEV study to determine cause and fix
  - A procedure to verify that the abort system is working properly.
    - Examine the possibility of a hardware system that can detect if the abort system is functioning
- Tevatron Beam Energy
  - 1MegaJoule in beam energy
  - Review of the policy for masking aborts
  - Reduce the time between the initiation of beam loss and abort
  - Quench protection upgrade solved the problem



Peak Luminosity



Integrated Luminosity



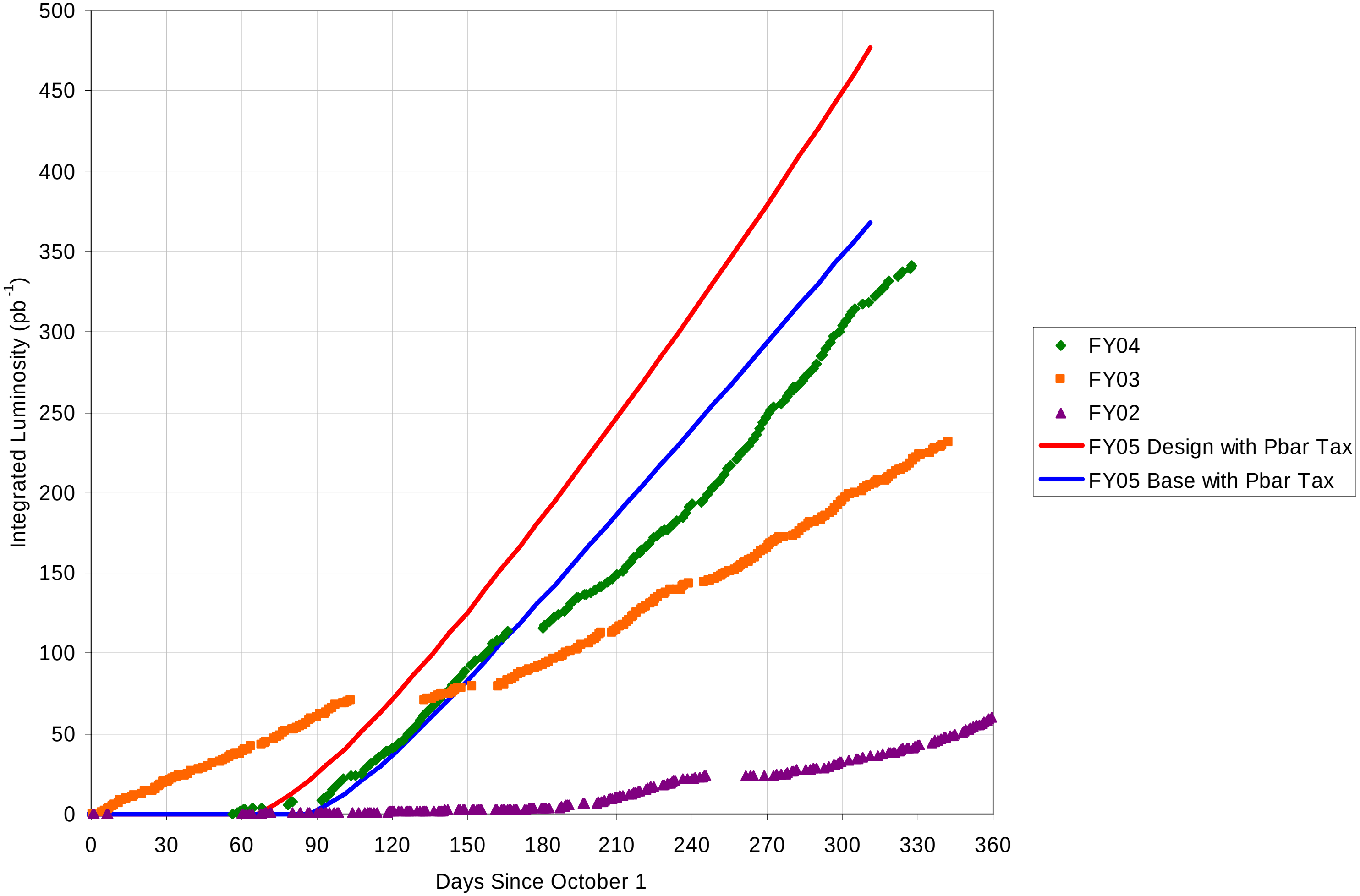
FY04 Summary

- Collider performance in FY04
  - Delivered 345 pb^{-1} in 39 weeks (8.8 pb^{-1} per week)
  - The peak luminosity and the luminosity per week has doubled from FY03
  - Most of the Tevatron parameters are close to the design values
  - The Proton Source is operating at record intensities, efficiencies, and throughput.
  - Slip Stacking has been commissioned in the Main Injector
  - The Recycler was:
    - ready for electron cooling
    - Dramatically increased peak luminosity through mixed-pbar operations
  - Pbar production is well below the design parameters but the study plan executed over the summer indicates that the source of the shortfall is the result of a small effective aperture in the D-A line
- FY05 will be a pivotal year for the Run II Collider
  - Pbar stacking
  - Mixed Pbar operation
  - Electron cooling installation and commissioning
  - NUMI Commissioning and Running
  - MiniBoone and SY120 continue
    - Not enough protons to go around

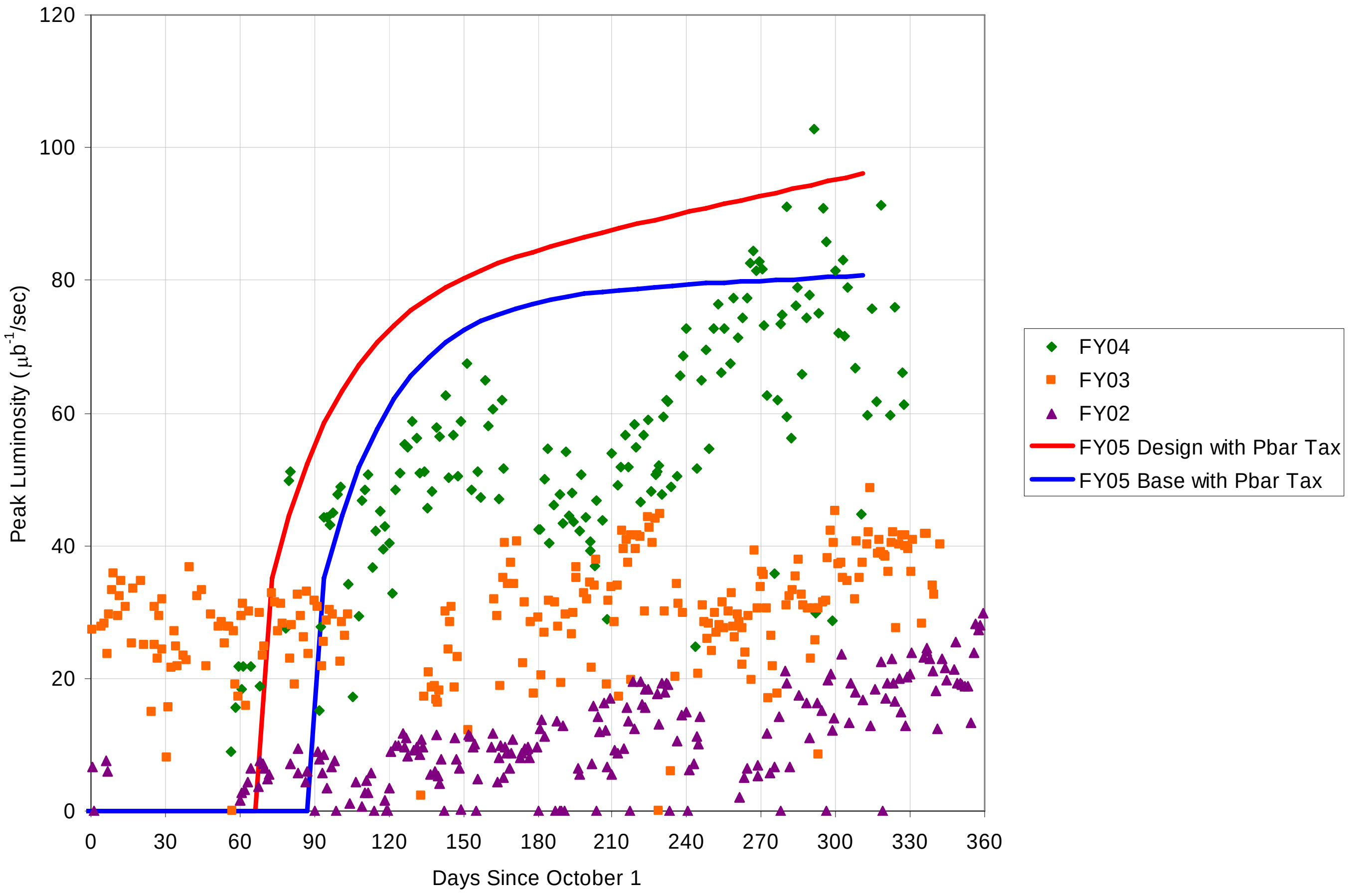
Plans for FY05

- Demonstrate electron cooling of antiprotons by the end of FY05
- Run Slip Stacking at 8×10^{12} protons/pulse every 2 secs
- Increase the pbar production aperture by 25%
- Stack at small stacks with a rate of $18\text{-}24 \times 10^{10}$ pbars/hr
- Run the complex in Mixed Pbar operations
  - Assume the gain from Mixed Pbar operations is at least “break-even” on integrated luminosity
- Run NUMI at a 2 sec. cycle time with 2.5×10^{13} protons/cycle by the end of the year
  - Keep activation levels in Booster at the April 29, 2004 level.
- Continue to run MiniBoone and SY120
  - Will need guidance from Program Planning on the priorities of NUMI, MiniBoone, SY120
- Integrate $470 pb^{-1}$ in 34 weeks (average $\sim 14 pb^{-1}$/week)

FY05 Goals Integrated Luminosity



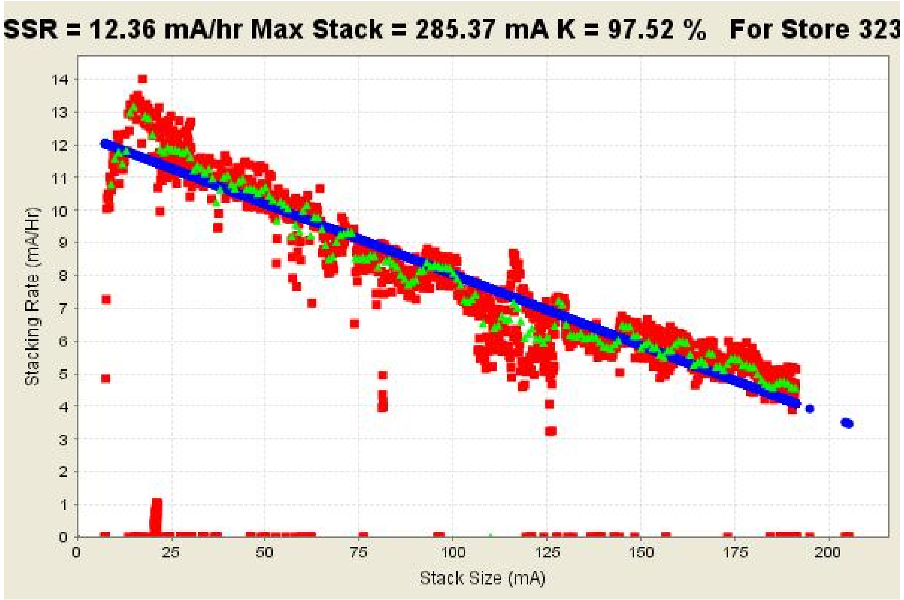
FY05 Goals Peak Luminosity

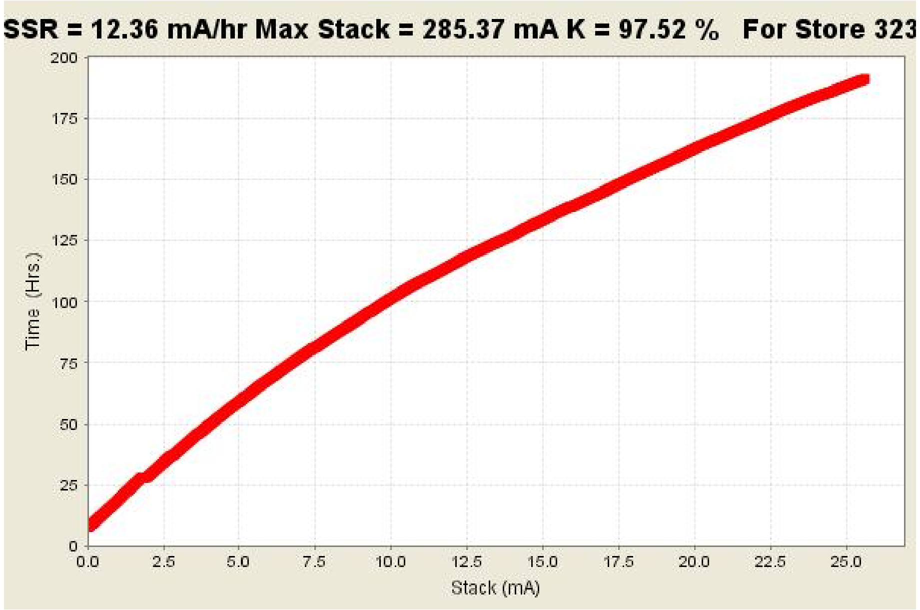


Combined Shots

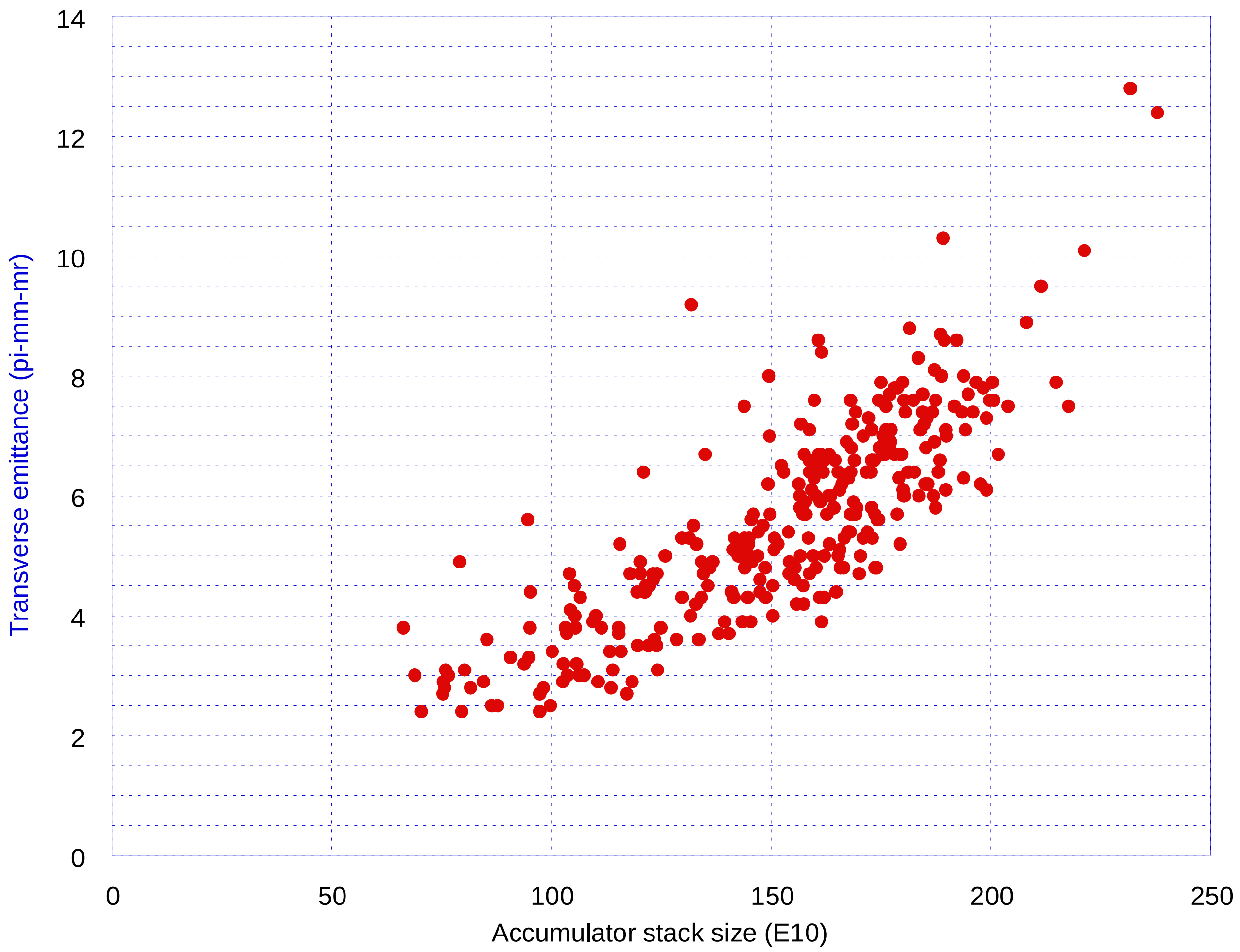
- Extracting antiprotons from both the Accumulator and the Recycler for the same store i.e.
  - Twelve bunches from the Recycler
  - Twenty four bunches from the Accumulator
- Combined Shot Operation
  - Proposed in February ’04
  - Initial proposal presented at the April ’04 Run II PMG
  - Dual energy ramps in the MI completed and tested by May ’04
  - First Attempt 6/13/04
  - Record Luminosity
    - $103 \times 10^{30} cm^{-2} sec^{-1}$ recorded July 2004
    - $127 \times 10^{30} cm^{-2} sec^{-1}$ recorded May 2005
  - Routine Operations - January 2005
- Reasons
  - Flexibility in the Run II Upgrade schedule
    - Natural merging of commissioning of electron cooling
  - Push Recycler commissioning progress by plunging it into operations
  - Luminosity enhancement – larger amount of antiprotons for smaller emittances
    - Accumulator stack size limited to <200 mA
      - Stacking Rate
      - Transverse emittance vs Stack Size
- Ratio $I_{Recycler}/I_{Accumulator}$ is governed by:
  - Recycler phase space density (cooling)
  - Recycler transfer time (Rapid transfers)
- Obstacles
  - Stacking Rate
  - Injector Complex 8 GeV energy alignment
  - Longitudinal emittance in both the Accumulator and Recycler
  - Transfer time between Accumulator to Recycler

Pbar stacking performance

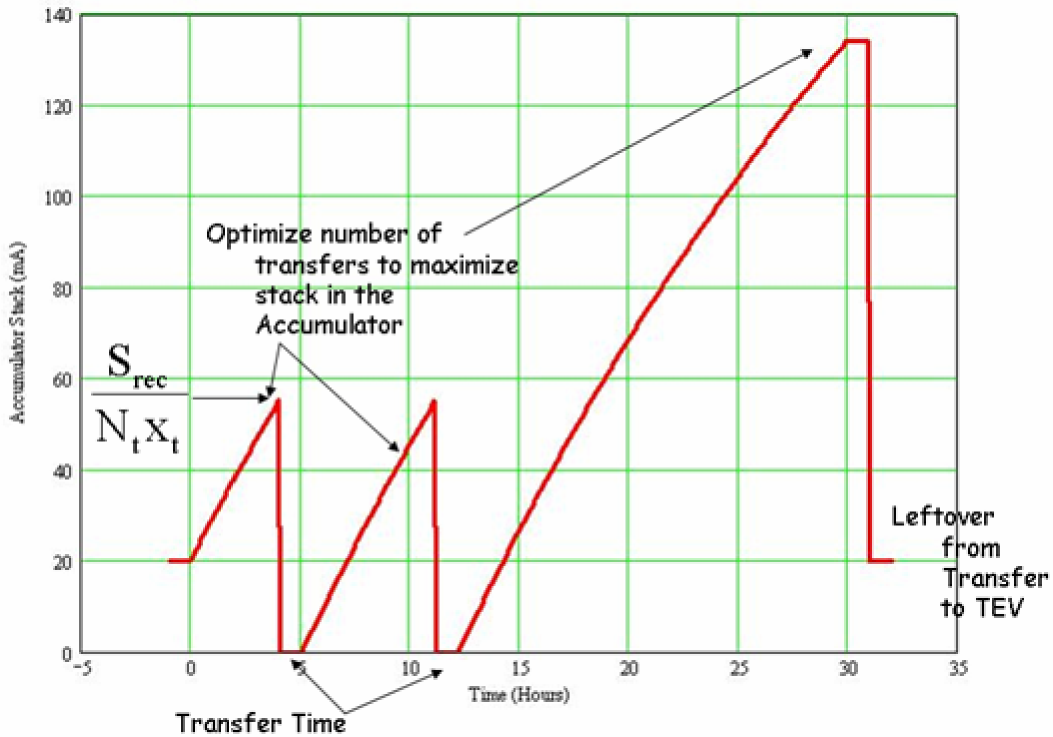




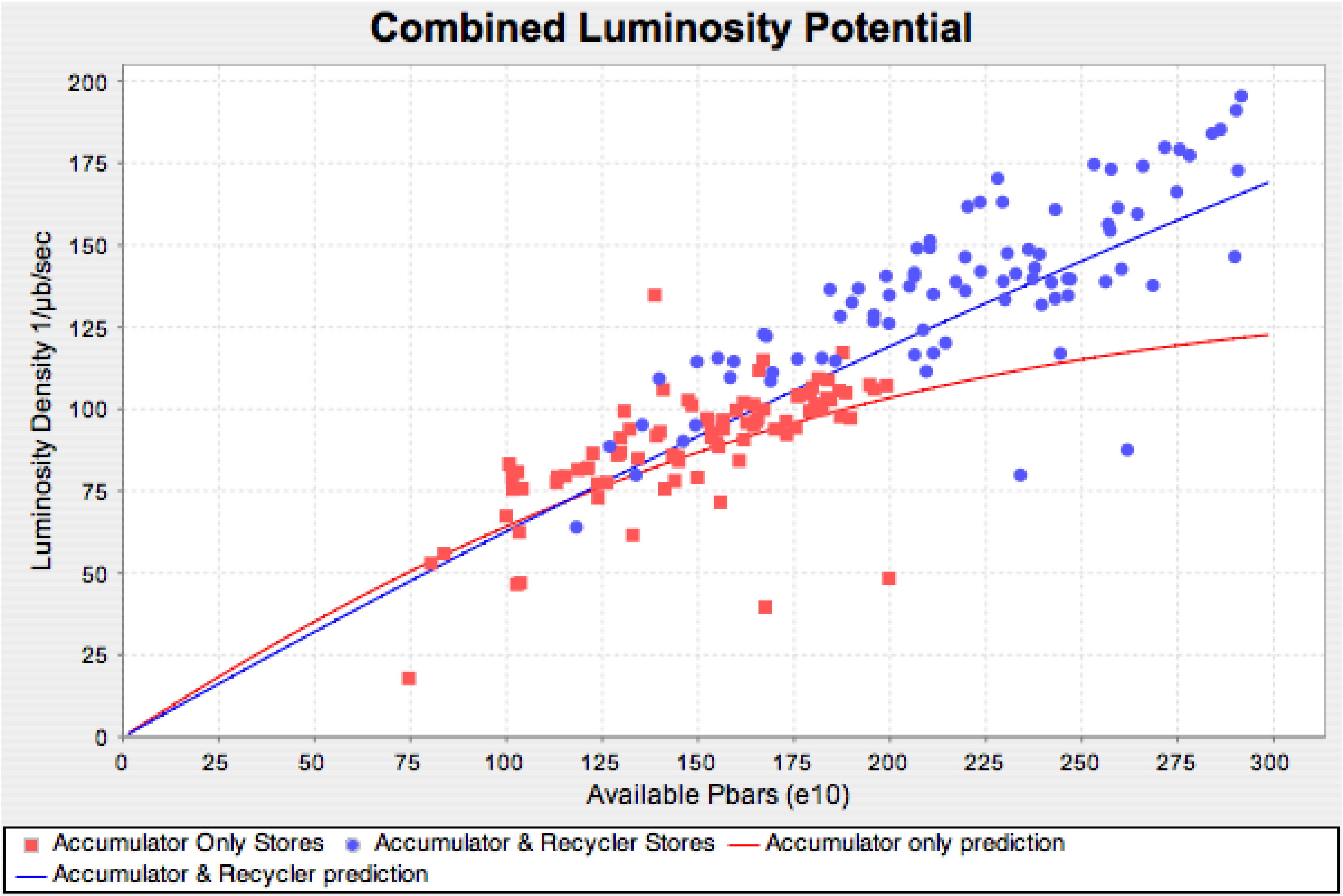
Accumulator Stack Size vs. Transverse Emittance



Accumulator to Recycler Antiproton Transfers

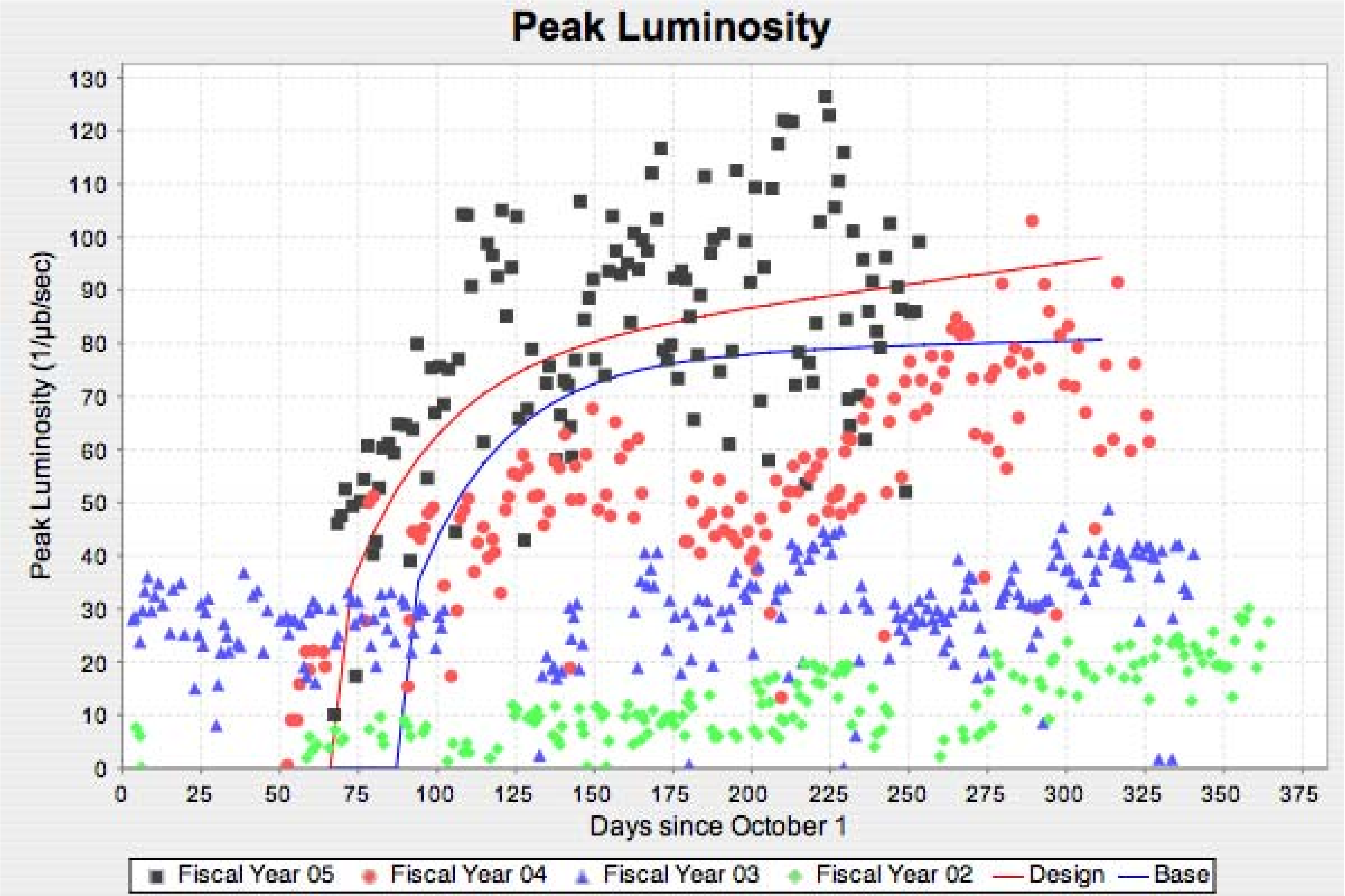


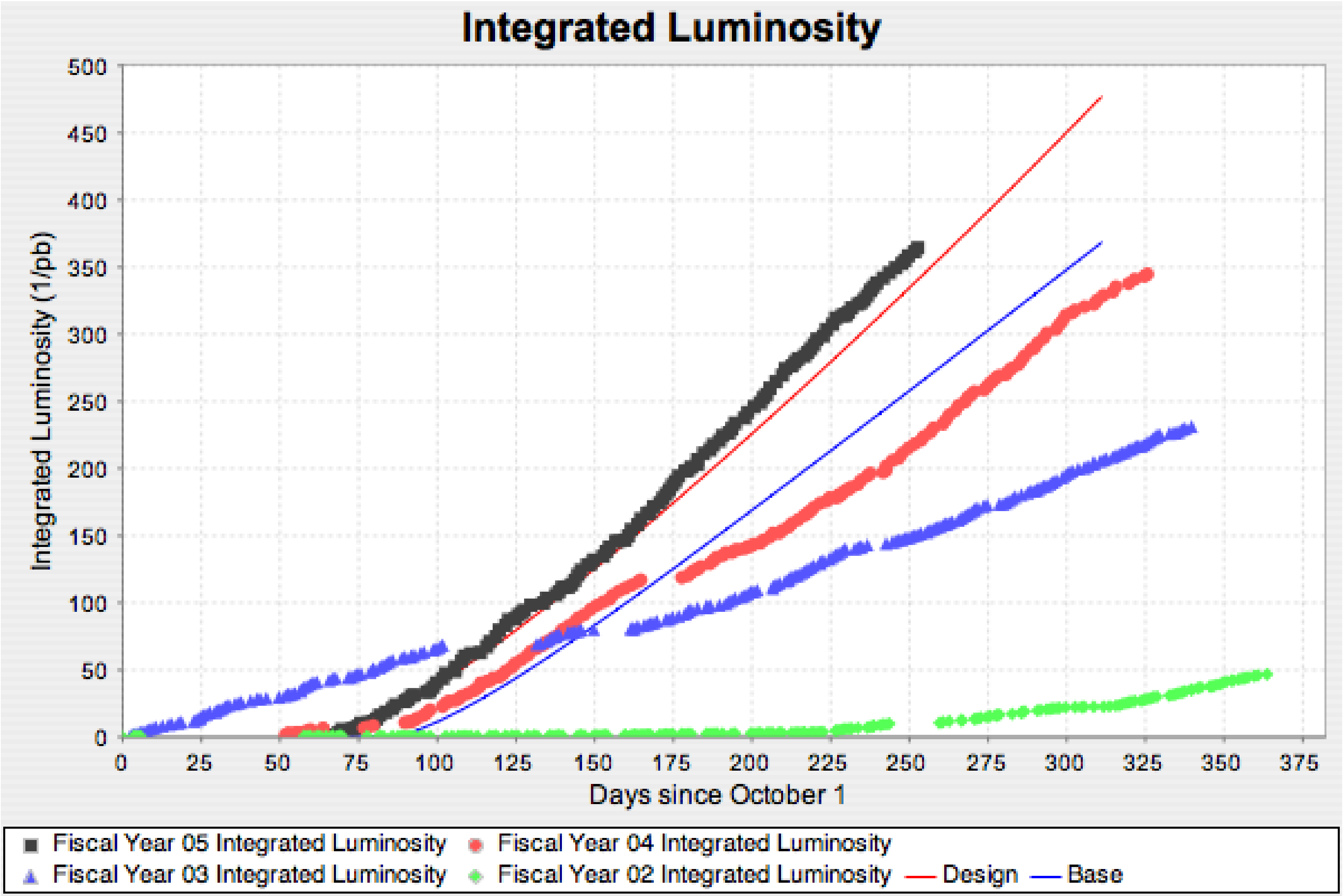
- Transfers between the Accumulator to the Recycler take about 1 hour to accomplish
  - Presently 1 or 2 sets of transfers to support a collider store
- To realize the full potential of electron cooling, in the Recycler, this time needs to be reduced to less than 15 minutes with >90% efficiency
- Adopt a philosophy of being willing to lose a pbar transfer occasionally
  - Transfers frequency eventually faster than every 2 hours


Combined Luminosity Potential
Luminosity Density 1/µb/sec
Available Pbars (e10)
0
25
50
75
100
125
150
175
200
225
250
275
300
Accumulator Only Stores
Accumulator & Recycler Stores
Accumulator only prediction
Accumulator & Recycler prediction

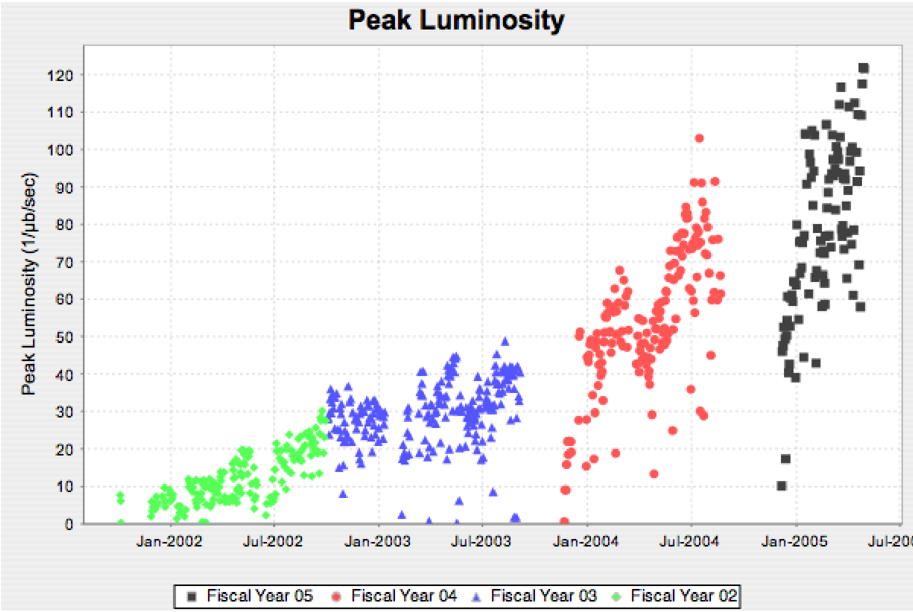
Electron Cooling

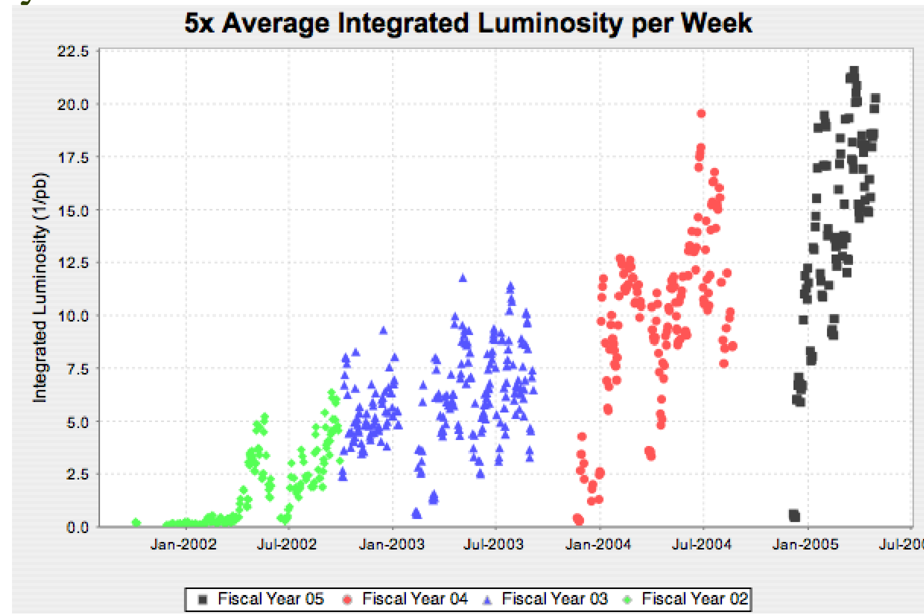
- The maximum antiproton stack size in the Recycler is limited by
  - Stacking Rate
  - Longitudinal cooling in the Recycler
- Longitudinal stochastic cooling of 8 GeV antiprotons in the Recycler is to be replaced by Electron Cooling
  - Electron beam: 4.34 MeV – 0.5 Amps DC – 200μrad beam spread – 99% recirculation efficiency
- Installation of e-cool equipment in MI-31 and the Recycler tunnel complete
- Commissioning of electron cooling in progress
  - Electron beam circulated in cooling section
  - Commissioning due to be completed by September 2005


Peak Luminosity
Peak Luminosity (1/µb/sec)
130
120
110
100
90
80
70
60
50
40
30
20
10
0
0
25
50
75
100
125
150
175
200
225
250
275
300
325
350
375
Days since October 1
Fiscal Year 05
Fiscal Year 04
Fiscal Year 03
Fiscal Year 02
Design
Base


Integrated Luminosity
Integrated Luminosity (1/pb)
0
50
100
150
200
250
300
350
400
450
500
0
25
50
75
100
125
150
175
200
225
250
275
300
325
350
375
Days since October 1
Fiscal Year 05 Integrated Luminosity
Fiscal Year 04 Integrated Luminosity
Fiscal Year 03 Integrated Luminosity
Fiscal Year 02 Integrated Luminosity
Design
Base

Luminosity in Run II



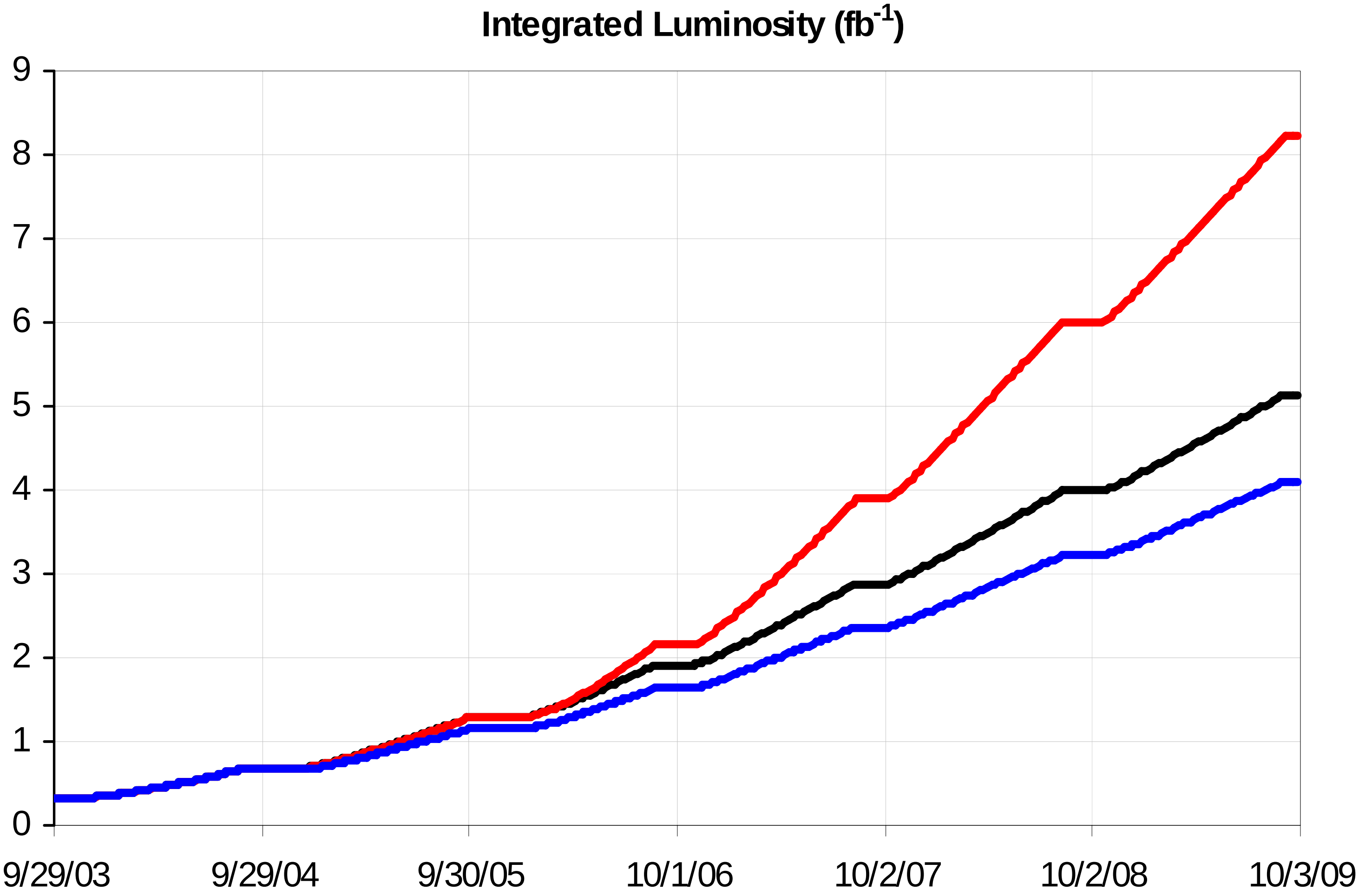


- Luminosity increase is mostly due to:
  - Decision to “run” the Collider
    - Rigorous approach to attacking operational problems
    - De-emphasis of long periods of dedicated machine studies
  - Better performance of the injector chain
    - Faster pbar stacking because of increased protons on target
  - Alignment of the Tevatron
  - Introduction of the Recycler into operations

Other Business - Fixed Target FY05 Accomplishments

- Record throughput for MiniBoone
  - 8.0×10^{16} protons/hour
  - Delivered a over 5×10^{20} protons in under three years of running
- Routine running of Mixed Mode for SY120 with slip-stacking for pbar production
  - A factor of 7 more spill seconds then originally allocated
    - And they're still unhappy
  - NUMI has taken the place of SY120 on the antiproton stacking cycles, a new long flattop ramp has kept about half of the spill-seconds intact (with a 5% hit to NuMI and pbar production).
- NUMI commissioned
  - First beam on Dec. 4, 2004
  - Around the clock operations on March 14, 2005
  - Target problems April 2005
  - Have resumed operations in Mixed-Mode antiproton stacking cycles

Integrated Luminosity in Run II



Summary

- Since last year's retreat, the Tevatron has seen:
  - 60% increase in peak luminosity
  - 40% increase in integrated luminosity per week
  - 100% increase in integrated luminosity for Run II
- Luminosity increase is mostly due to:
  - Better performance of the injector chain and faster stacking (up to 16E10/Hr)
  - Introduction of the Recycler into operations
  - Decision to "run" the Collider
    - Rigorous approach to attacking operational problems
    - De-emphasis of long periods of dedicated machine studies
- The Run II Upgrades are on track to provide more than 4fb^{-1} by 2009
  - The Recycler is operational
  - Electron cooling is progressing well
  - Slip Stacking is operational
- The major challenges left in Run II centers on antiprotons
  - Commission electron cooling in the Recycler
  - Increase the antiproton production rate
    - AP2- Debuncher aperture upgrade, Lens upgrade
    - Debuncher to accumulator transfers, stacktail momentum upgrade
    - More protons on target with acceptable losses in the Main Injector
    - Rapid transfers between the Accumulator and Recycler, fast and efficient